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Stability Analysis of Composite Breakwater with Wave-Dissipating Blocks considering Increase in Sea Levels, Surges and Waves due to Climate Change

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Abstract: Settlement of wave-dissipating blocks in front of a caisson is caused by displacement and breakage of blocks directly by wave action and also by sliding of the caisson by wave force. The settlement of blocks, caisson sliding and wave pressure are mutually correlated. The present study has developed a stability analysis method for a composite breakwater with wave-dissipating blocks under the circumstances of climate change effect as seen in sea level rise and increase in storm surges and waves. It is found that the changes of expected caisson sliding distance and necessary caisson width, determined from the allowable excess probabilities for three prescribed sliding distances, against the weight of wave-dissipating block have a tendency to be maximum at certain block weight when repairing of damaged blocks is not done; on the other hand, if repairing is done every time after reaching 5 % damage level of total section, the changes of caisson sliding distance and necessary caisson width against the block weight show monotonous decrease. The effects of climate change on the sliding distance and necessary width are found to make those values larger 10 ~ 60 % than those calculated by constant external forces given from the present climate conditions.

Key Words: composite breakwater, wave-dissipating block, breakwater stability analysis, sea level rise, surges and waves, climate change

1. INTRODUCTION

It is pointed out that sea level rise and extremeness of tropical cyclones become noticeable in recent years due to climate change. Coastal external forces against costal defense structures, affected by the climate change, are the sea levels, storm surges and high waves. Damage of coastal structures, coastal erosion, morphological change and coastal flood disasters are expected to increase due to sea level rise and stormy wave climates. Therefore, researches of coast hazard evaluation accompanying with the change of atmosphere and ocean conditions due to climate change become important and have been carried out. The present study takes into consideration of the effects of climate change on a stability analysis of composite breakwater.

Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2007) by OCDI (The Overseas Coastal Area Development Institute of Japan) provided a guideline of performance design for coastal and harbor structures. The Technical Standards shows a design method of breakwaters using partial factors based on Level I reliability analysis and allowable excess probability of a given sliding distance based on Level III reliability analysis, during a service time of the breakwater. A reliability analysis is a useful method in the performance design of various kinds of coastal structures.

Shimosako and Takahashi (2000) and Shimosako et al. (2006) and Takayama et al. (2007) proposed a performance design procedure that treats the expected sliding distance of a caisson in a service time to evaluate the stability of the breakwater. Shimosako et al. (2006) applied the reliability design to a breakwater armored with wave-dissipating blocks, where the damage and subsidence of block section were not considered. Takayama et al. (2007) extended Shimosako et al.'s method to include the effect of the subsidence of block section and the resulting effect of the increase in wave force due to the subsidence. There are few studies that deal with the effects of climate change for the design of a caisson breakwater. Okayasu and Sakai (2006) proposed a method to calculate the optimal cross section of a caisson considering sea-level rise. Takagi et al. (2011) reported that the expected sliding distance for a breakwater at a specific site becomes five times greater than that at present by a combination of increases in sea level rise and wave height. Suh et al. (2012) described how to incorporate the influence of climate change into the performance-based design. They analyzed the expected sliding distance and exceedance probability of an allowable sliding distance each year for the service time of the breakwater where the sea level rise, deepwater wave height and storm surge (defined as 10 % of wave height) were assumed to be changed as linear and parabolic manner, and showed that the effects of climate change dictated in no small increase of caisson width.

Since there are few studies of stability analysis for a composite breakwater armored with wave-dissipating blocks incorporated the changes of external forces accompanying with the climate change, the present study has developed a reliability analysis of estimating expected sliding distance and necessary caisson width by taking account of the change of sea levels, surges and waves during a service time.

2. RELIABITY ANALYSIS OF COMPOSITE BREAKWATER WITH WAVE-

DISSIPATING BLOCKS

2.1 Modeling of Blocks' Damage

The following empirical formula proposed by Takahashi et al. (1998) is used to estimate the degree of block damage:

$$N_s = \frac{H_{1/3}}{\{(\rho_s / \rho_w) - 1\} D_n} = C_H \left\{ a (N_0 / N^{0.5})^c + b \right\} \tag{1}$$

where N_S = the stability number, $H_{1/3}$ = the incident significant wave height at a breakwater, ρ_s = the mass density of concrete block, ρ_w = the mass density of water, D_n = the representative diameter of a concrete block, C_H = the reduction coefficient for wave breaking $\{=1.4/\ (H_{1/20}/H_{1/3})\}$, N_0 = the number of displaced blocks within a strip width of D_n by van der Meer (1987), and N = the number of waves. The coefficients of a, b and c are 2.32, 1.33 and 0.2 for Tetrapods with a 1:4/3 slope of block section. The empirical formula of Eq. (1) can estimate the cumulative number of displaced blocks for simulated storms by counting the number of acted waves as follows.

Let $N_0(i\text{-}1)$ be the cumulative number of displaced blocks up to a year ago, and $H_{1/3}(i)$ and $N(i)$ be the wave height and the number of waves for a present year. The equivalent number of waves, N', with $H_{1/3}(i)$ that causes $N_0(i\text{-}1)$ is obtained from Eq. (1) as

$$N' = \left(\frac{H_{1/3}(i) / [C_H \{(\rho_s / \rho_w) - 1\} D_n] - b}{a} \right)^{2/c} \left\{ N_0(i-1) \right\}^2$$

(2)

By using the wave height $H_{1/3}(i)$ and the waves' number $N(i)+N'$, the cumulative number of displaced blocks is calculated by

$$N_0(i) = \left(\frac{H_{1/3}(i) / [C_H \{(\rho_s / \rho_w) - 1\} D_n] - b}{a} \right)^{1/c} \left\{ N(i) + N' \right\}^{0.5} \tag{3}$$

for the present year's storm wave. Eqs. (2) and (3) provide the cumulative number of displaced blocks.

The subsidence of the crown height of block section is calculated from the volume of displaced blocks corresponding to the cumulative number of displaced blocks that assumed to be moved seaward.

2.2 Wave Force on Caisson with Wave-Dissipating Blocks

In addition to the subsidence of crown height of block section directly displaced by waves, it is assumed that the subsidence of the crown height is induced so as to fill the space volume between the original back-face location of block section and front-face location of the moved caisson. The subsidence of the crown height of block section intensifies wave force acting on the caisson. Takahashi et al. (2000) proposed a method to estimate the wave pressures for partially armored breakwaters that become insufficient to cover the caisson by the displacement of blocks. They assumed three regions where the intensity of impact wave pressure is different each other. Figure 1 shows a sketch of composite breakwater with wave-dissipating blocks. Impulsive wave pressures act in Region 1 and 2 when the caisson is un-armored and the modification coefficients to Goda's formula (2000) was proposed. Wave pressures in Region 3 are estimated by Goda's formula (2000). Since the modification coefficients for Region 1 and 2 by Takahashi et al. (2000) are lengthy, they are not described here. Figure 2 shows the change of wave pressure distributions from fully armored state to partially exposed state, in which the increase in wave pressures is seen in Region 1 and 2.

The time variation of wave pressure is given by the method by Tanimoto et al. (1996) in which standing wave pressure, double peak pressure, wave breaking pressure and impulsive wave pressure were modeled.

The armor concrete blocks are moved and settled down by storm waves. Their damage and subsidence intensify wave pressures on the caisson. Those intensified wave pressures promote the sliding of the caisson; the caisson sliding also makes the crown height set down, and furthermore intensifies wave pressures. In this study, the repairing of block section is carried out when the damage level to the total section reaches 5%; that is, the crown height of blocks is reset at the original position.

2.3 Reliability Analysis of Level III

The sliding distance is calculated from the wave forces. The mathematical model to calculate the sliding distance is seen many papers (e.g., Shimosako and Takahashi, 2000; Goda and Takagi, 2000; Goda, 2001; Kim and Takayama, 2003; Hong et al., 2004, Suh et al., 2012). The present study followed the existence procedure for calculation of sliding distance by the wave forces. The routine of estimating the subsidence of crown height of block section and the change of wave forces due to insufficient armor is added to the existing procedure.

In a reliability analysis of Level III, probability density functions (pdfs) of random variables are used to calculate a failure probability. The Monte-Carlo simulation is employed to give individual random values from the target pdfs. Although the present study does not use the failure function, the simulation procedure is the same as the reliability analysis. Figure 3 shows a flowchart to compute each sliding distance and expected sliding distance (average of repetition results) of caisson during a service time; 50 years is taken as the service time.

The flow using the Monte-Carlo simulation is as follows:

1. Setting of annual maximum wave from a given extreme distribution function
2. Calculation of wave height $H_{1/3}$ at a target breakwater location
3. Generation of individual waves from the Rayleigh distribution with $H_{1/3}$
4. Calculation of total sliding distance in a storm; at the same time, the damage degree and settlement are calculated for $H_{1/3}$
5. Calculation of cumulative slide distance and settlement of concrete blocks
6. Modification of wave pressures due to settlement of blocks
7. Procedures from 1 to 6 are repeated for service time

By repeating the above flow 10,000 times, the expected sliding distance of a caisson and excess probability of a specific sliding distance are obtained.

3. SETTING OF EXTERNAL FORCES

3.1 Sea Level Rise (SLR)

The influences of global climate change due to greenhouse effects will be noticeable in recent years. The sea level rise is static issue of climate change and is important for human activity near the coastal zone. A global sea level increased by 1.8mm/year from 1961~2003 and 3.1mm/year from 1993~2003 (IPCC, 2007), and IPCC AR4 denotes that the projected maximum and minimum sea level rise at the end of 21st century are 0.18m and 0.59m depending on different scenarios and general circulation model outputs.

On the other hand, it is not appropriate using the global value for regional impact assessment. Mori (2012) and Mori et al. (2013) summarized the sea level rise by arranging all available CMIP3 models for A2, A1B and B2 scenario around Japan. Figure 4 shows Japan region outputs from CMIP3 for A1B scenario. The mean SLR trend around Japan is slightly different from the global trend, and the standard deviation between the models is two times larger than that of global value (Mori et al., 2012). The present study uses the ensemble mean value of 0.26 mm/year for the sea level rise around Japan.

3.2 Storm Surges

Projection of future change of storm surges is difficult due to the randomness of typhoon occurrence and strong dependence of typhoon track (e.g. Mori, 2012). There are several studies to project regional future storm surges accompanying with the change of typhoon characteristics (e.g., Kawai et al., 2007, 2009; Yasuda et al., 2009). Since Kawai et al. (2007) showed how storm surge heights will change corresponding to future typhoons under A2 scenario, the present study followed the result by Kawai et al. (2007). Figure 5 displays the occurrence probability density functions of surge heights at Osaka Bay, Japan, in present climate and future climate at the end of 21st century. The pdfs, shown below, are used as the extreme distributions in this study.

$$F(x) = 1 - \exp\left\{ -\left(\frac{x + 0.248}{0.998} \right)^{1.4} \right\} \quad \text{; for present climate} \qquad (4)$$

$$F(x) = \exp\left[-\exp\left\{ -\left(\frac{x - 0.358}{0.646} \right) \right\} \right] \quad \text{; for future climate} \qquad (5)$$

3.3 Storm Waves

Mori et al. (2010a, 2010b) investigated future ocean wave climate in comparison with present wave climate based on an atmospheric general circulation model and global wave model under A1B scenario. They showed that future change of averaged wave height depends on latitude strongly. On the other hand, the extreme wave height in the future climate will increase significantly in tropical cyclone prone areas. They also provided extreme distributions of wave heights in summer and winter season, considering the different weather systems, by using the peak over threshold approach (POT). The POT approach counts maximum values of each storm event and it is possible to increase the number of events rather than annual maximum. The storm is defined as the sequence of values exceeding a certain high threshold. The estimated statistical extreme distributions are shown in Fig. 6 (a) for summer season and Fig. 6 (b) for winter season; those are described by

$$F1(x) = 1 - \exp\left\{ -\left(\frac{x - 7.74}{4.02} \right)^{1.0} \right\} \quad ; \quad \text{for summer season in present climate} \qquad (6)$$

$$F2(x) = 1 - \exp\left\{ -\left(\frac{x - 5.72}{1.80} \right)^{1.4} \right\} \quad ; \quad \text{for winter season in present climate} \qquad (7)$$

$$F1(x) = 1 - \exp\left\{ -\left(\frac{x - 7.58}{5.25} \right)^{1.0} \right\} \quad ; \quad \text{for summer season in future climate} \qquad (8)$$

$$F2(x) = 1 - \exp\left\{ -\left(\frac{x - 6.03}{1.26} \right)^{1.0} \right\} \quad ; \quad \text{for winter season in future climate} \qquad (9)$$

The cumulative distribution for two mixed populations is given by

$$F(x) = \exp\left\{ -\sum_{j=1}^{2} [1 - F_j(x)] \right\} \qquad (10)$$

where $F(x)$ is the cumulative distribution of annual maxim and $F_j(x)$ is that for summer and winter seasons' extreme distributions. By using Eq. (8), Random variable can be generated in the Monte-Carlo simulation.

3.4 Change of External Forces during Service Time

The values of sea level rise, surge heights and wave heights are assumed to change linearly from the present climate and to the future one:

$$H(p) = H_p(p) + \frac{y}{Y}\left[H_f(p) - H_p(p)\right] \tag{11}$$

where $H_p(p)$ is the value with the occurrence probability of p in the present climate, $H_f(p)$ the value in the future climate, Y is set to 100 (years) and y is the passage year. Though there are several choices of time trend as linear, exponential, and quadratic increase, the present study adopted only the linear increase. This choice may larger impact compared to the other choices. In addition to the time trend, there are many factors which affect the results: different GCM outputs under different scenarios. The present study used a GCM projection by Meteorological Research Institute (Japan Meteorological Agency) under A1B scenario. The results of GCM model ensemble and scenario ensemble should be examined to provide a mean values and variation, but not carried out here.

3.5 Calculation Conditions

Table 1 shows the calculation conditions of the offshore design wave height in summer and winter season for the present and future climate, the installed water depth of breakwater, the design caisson width, the crown height, the storm surge height for the present and future climate, the sea level rise, the duration period of one storm, the service time of breakwater, the repetition number of Monte-Carlo simulation, the criterion of damage level required for repairing armor blocks. Noted that the design caisson width are determined by a conventional design method to have SF=1.2 (Safety Factor) for the design wave at the breakwater estimated through wave transformation of shoaling and wave breaking with the refraction coefficient of K_r = 1.0 and 0.5 in the present climate where the surge height is not included. The duration time of one storm is 2 hours. Each wave period was set so as to be the wave steepness of 0.033 depending on each wave height. The coefficient of friction factor for sliding is given by a Gaussian distribution with the mean value of 0.6 and standard deviation of 0.16.

The weight of blocks is changed as 16 kinds from 2 t to 80 t. Two cases are analyzed without and with repairing of block section when the damage percent reaches 5 %. The repairing means that the crown height of blocks is reset at the original position. Figure 7 shows the cross section of model breakwater used in this study.

4. RESULTS

4.1 Expected Sliding Distance of Caisson

Figure 8 shows the expected sliding distance of a caisson against the block weight for three kinds of installed water depth when K_r=0.5; (a) is for 7 m, (b) 10 m, and (c) 15 m. In these figures, the results of expected sliding distance with and without considering the climate change effects and the repairing of block section are shown by different symbols. When the repairing is not done, the expected sliding distance shown by solid and open circles has maximum for a certain block weight of 12 t in the case of 7 m water depth, 16 t in the case of 10 m water depth, and 20 t in the case of 15 m water depth. The reason why being a maximum in Fig. 8 is as follow. Since when the block weight is small, the damage becomes large and the settlement of blocks becomes large, the regions where impulsive wave pressures act on the caisson become smaller and the sliding distance becomes small. As the result there appears a maximum in the change of sliding distance against the block weight; that is, sliding, settlement and pressure are correlated.

If the repairing is done when the damage level reaches 5 %, the expected sliding distance of caisson decreases with the increase in block weight except the case of installed water depth 7 m and smaller block’s weight than 4 t, as shown by solid and open triangles.

When comparing the results with and without taking into consideration of climate change effects, the expected sliding distances with climate change effects are 10 ~ 60 % larger than those without climate change effects. The result is shown clearly in the Chapter 5.

4.2 Necessary Width of Caisson

Figure 9 shows the necessary caisson width that satisfies the allowable excess probabilities for specified sliding distances when K_r=0.5. The allowable excess probabilities are denoted in Table 2 proposed by Shimosako and Tada (2003). The present study adopted the values for Importance Level 2 (Ordinary). As like the expected sliding distance, the necessary caisson width has the maximum against the block weight; however, the block weight at the maximum caisson width is different from that obtained for the expected sliding distance. Comparing the caisson width determined by the conventional design method using safety factor with that by performance design method using allowable distance and excess probability, the conventional method gives underestimations for all three cases of installed water depths 7 m, 10 m and 15 m.

5. EFFECT OF CLIMATE CHANGE ON BREAKWATER STABILITY

The ratio of expected sliding distance of caisson with and without including climate change effects is shown in Fig. 10 (a) where the horizontal axis is taken as the normalized water depth by the wave height at the breakwater to see the effect of water depth for both cases of K_r=0.5 and 1.0. When we take into consideration of climate change effects such as sea level rise and increase in storm surge heights and wave heights, the expect sliding distance increase 10 ~ 60 % compared to the results without increase of external forces. The ratios increase as the normalized water depth becomes large for the case of no-repairing, although the range is limited between 1.0 and 1.5. When the water depth is large, the wave height will increase due to the climate change effect since wave heights are not limited by wave breaking. The case of repairing shows a little higher value of the ratio showing constant against the normalized water depth. The necessary caisson width will also increase 10 ~ 20 % in spite of no-repairing and repairing, as shown in Fig. 10 (b).

The above results came from the conditions described in the Chapter 3. Since the present analysis method is easily able to be modified when the information of external forces accompanying with climate change and conditions of target breakwater; we can estimate how the impacts of climate change on a breakwater stability are severe by using updated information.

6. CONCLUSIONS

This study has analyzed the stability of composite breakwater with wave-dissipating blocks, based on a reliability analysis, by estimating a sliding distance of a caisson with and without considering the repairing of block section and the effects of climate change such as the sea level rise, storm surge heights and wave heights. It was found that the changes of expected sliding distance and necessary caisson width, determined from the allowable excess probabilities for prescribed sliding distances, against the weight of wave-dissipating block have a tendency to be maximum at a certain block weight when repairing of damaged block section is not done; on the other hand, if repairing is done after reaching 5 % damage level of total section, the changes of caisson sliding distance and necessary caisson width against the block weight show monotonous decrease.

When the proposed method takes into consideration of climate change effects such as sea level rise and increase in storm surge heights and wave heights, the expect sliding distance increase 10 ~ 60 % compared to the results without increase of external forces, and the necessary caisson width will increase 10 ~ 20 %.

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Captions of figures

Figure 1. Three different regions regarding intensity of wave pressure

Figure 2. Distribution of wave pressures in fully and partially covered with blocks

Figure 3. Flow of estimating expected sliding distance

Figure 4. Sea level rise adjacent Japan seas (Mori et al., 2012) (bccr: Bjerknes Centre for Climate Research; giss: NASA Goddard Institute for Space Studies; miub: Meteorologisches Institut der Universitat Bonn; ukmo: UK Met Office)

Figure 5. Probability density functions of present and future surge heights (Kawai et al., 2007)

Figure 6. Probability density functions of extreme wave height distribution; (a) summer season; (b) winter season (Mori et al., 2010)

Figure 7. Cross section of model breakwater

Figure 8. Expected sliding distance of caisson; (a) installed water depth of 7m; (b) installed water depth of 10m; (c) installed water depth of 15m

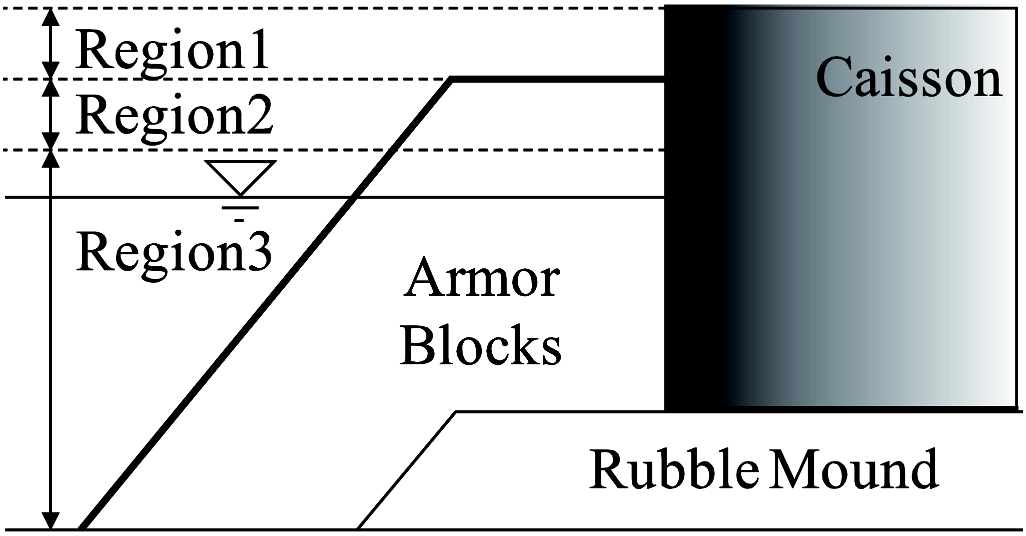
Figure 9. Necessary caisson width; (a) installed water depth of 7m; (b) installed water depth of 10m; (c) installed water depth of 15m

Figure 10. Effects of climate change for expected sliding distance and necessary caisson width; (a) sliding distance; (b) necessary caisson width

Caption of tables

Table 1 Calculation conditions

Table 2 Allowable sliding distance and excess probability



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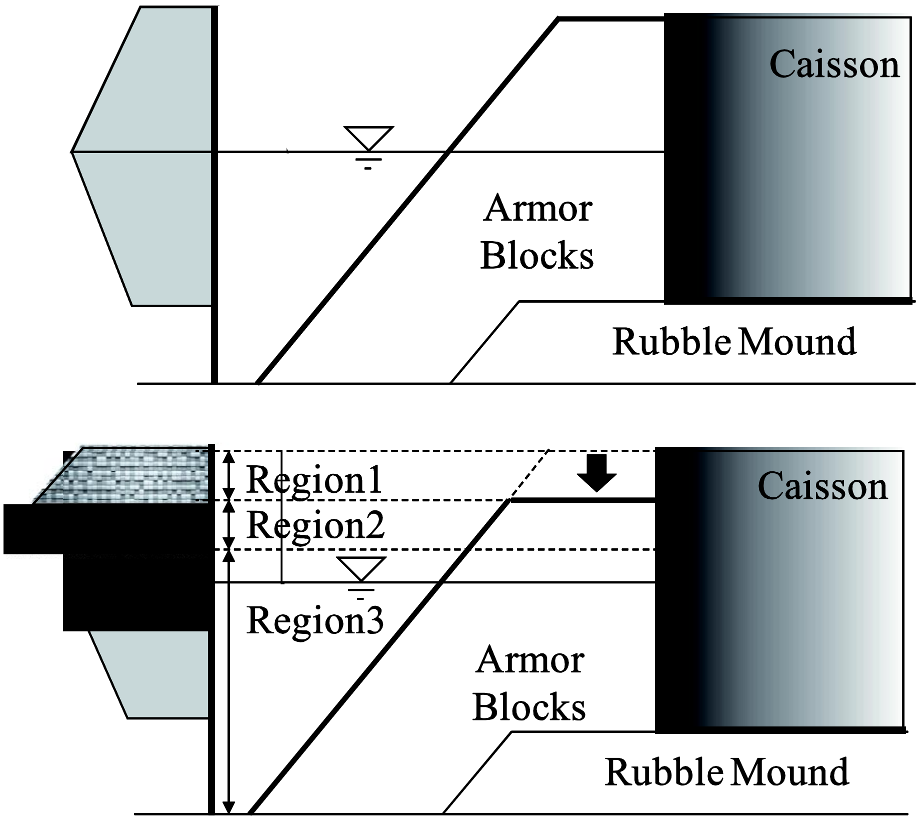


Figure 2. Distribution of wave pressures in fully and partially covered with blocks

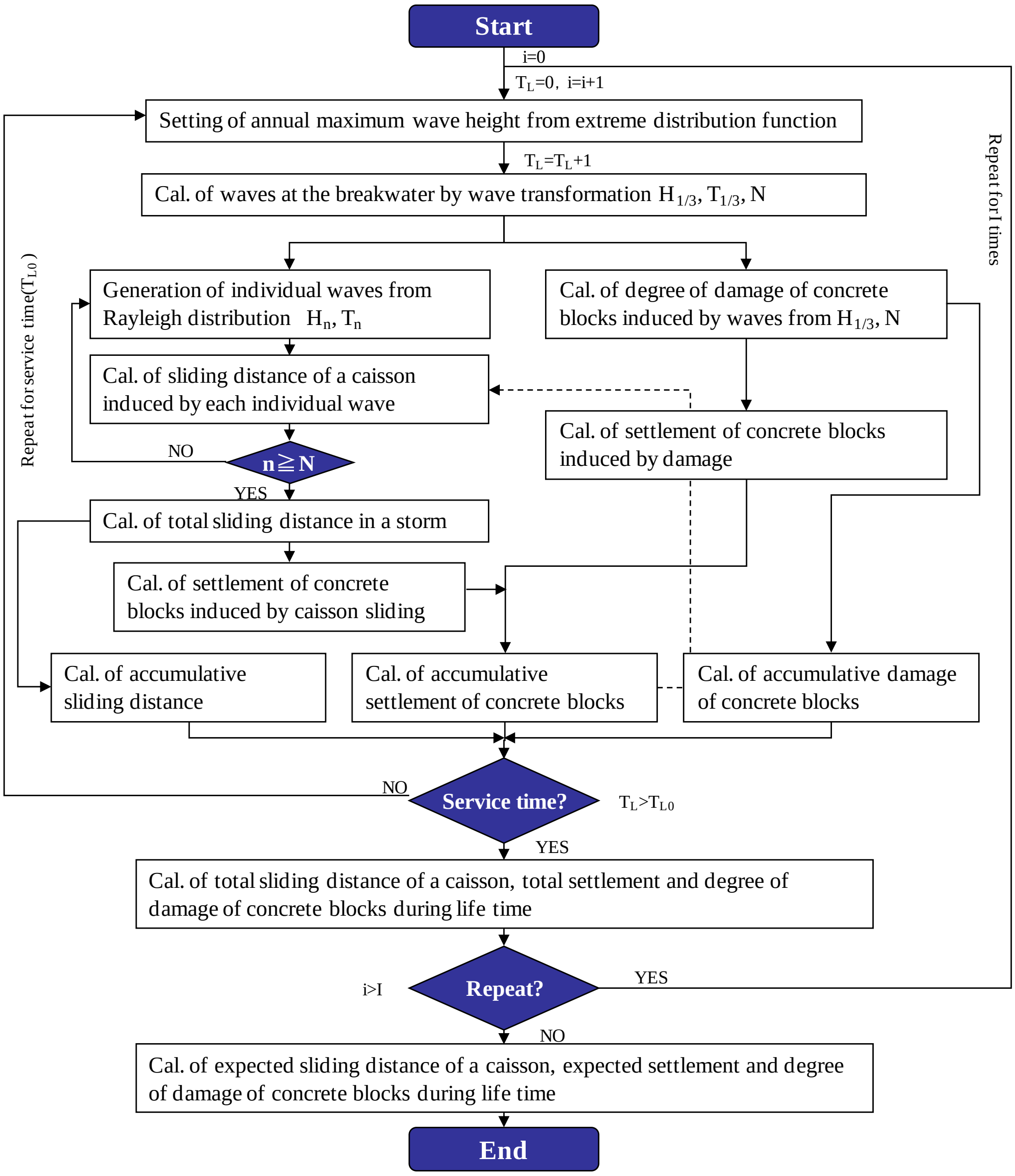
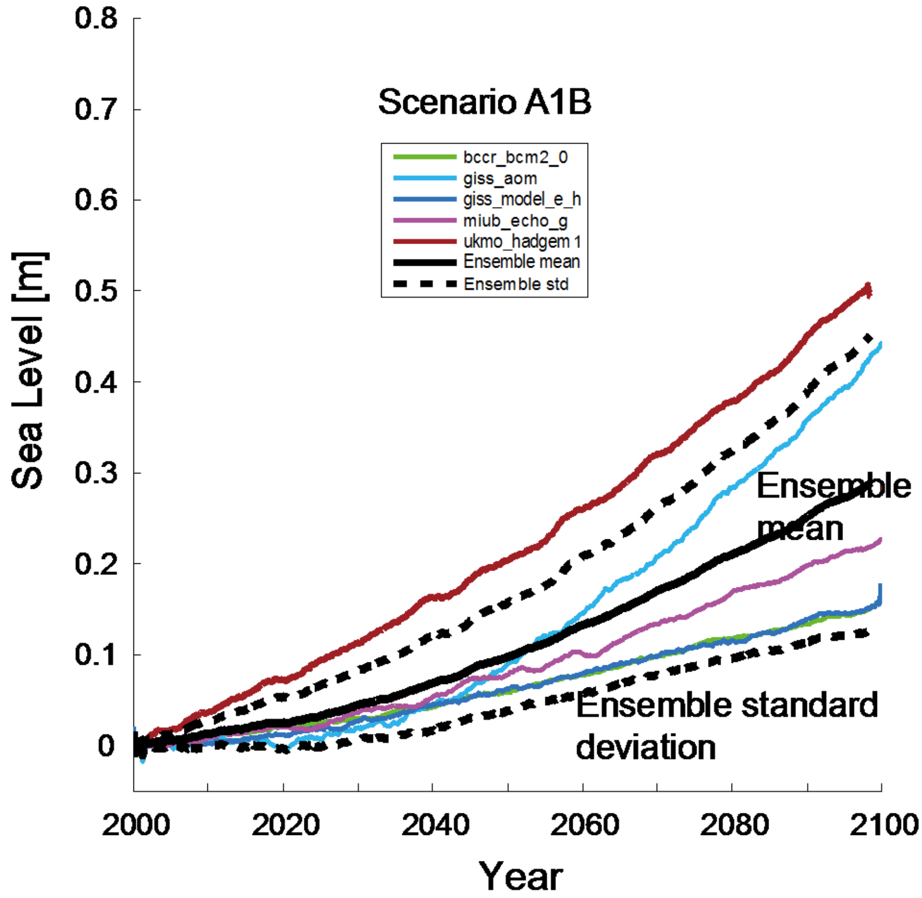


Figure 3. Flow of estimating expected sliding distance



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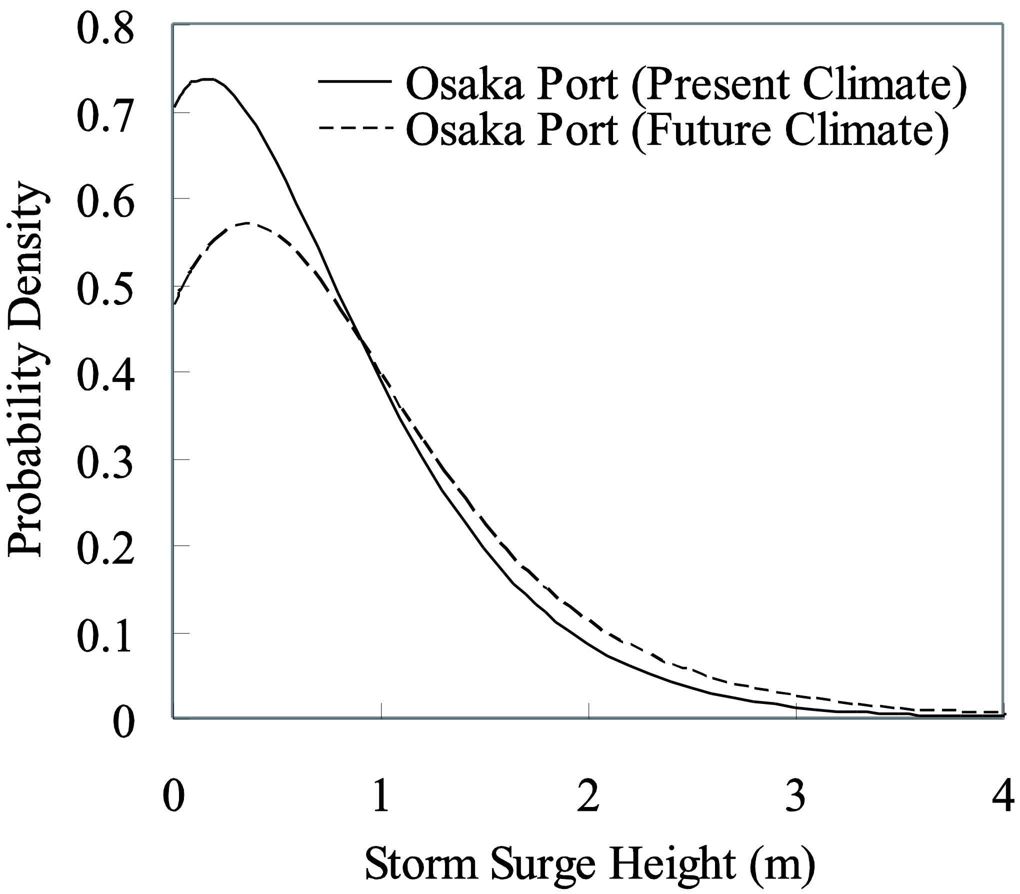

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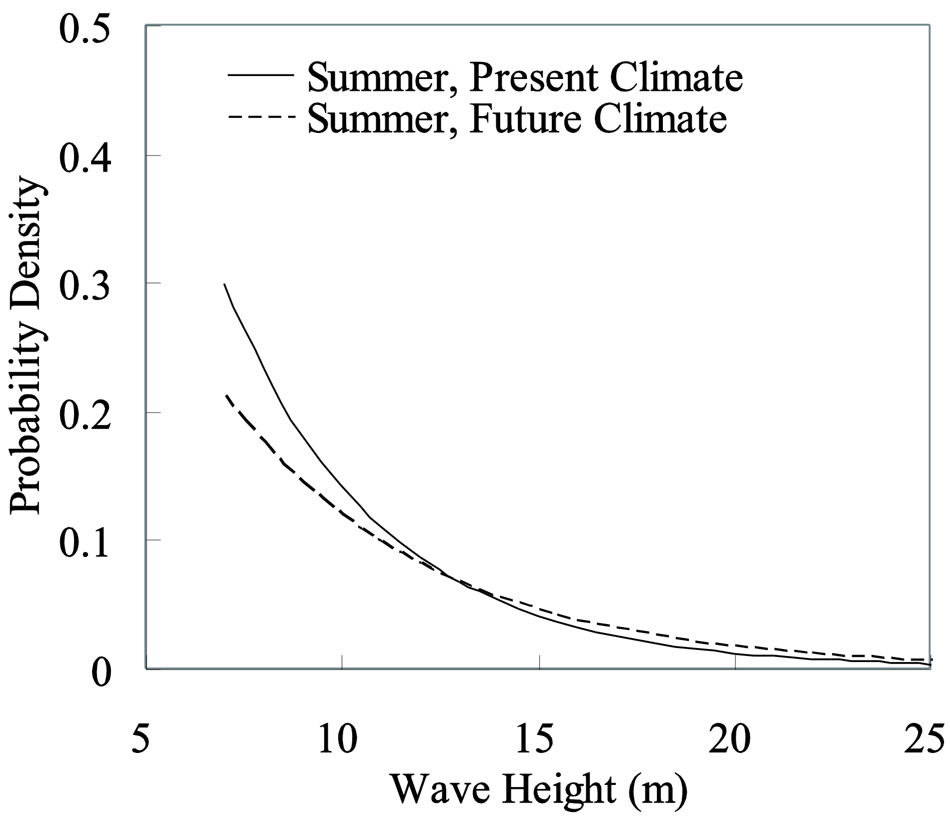


Figure 6 (a). Probability density functions of extreme wave height distribution; (a) summer season; (b) winter season (Mori et al., 2010)

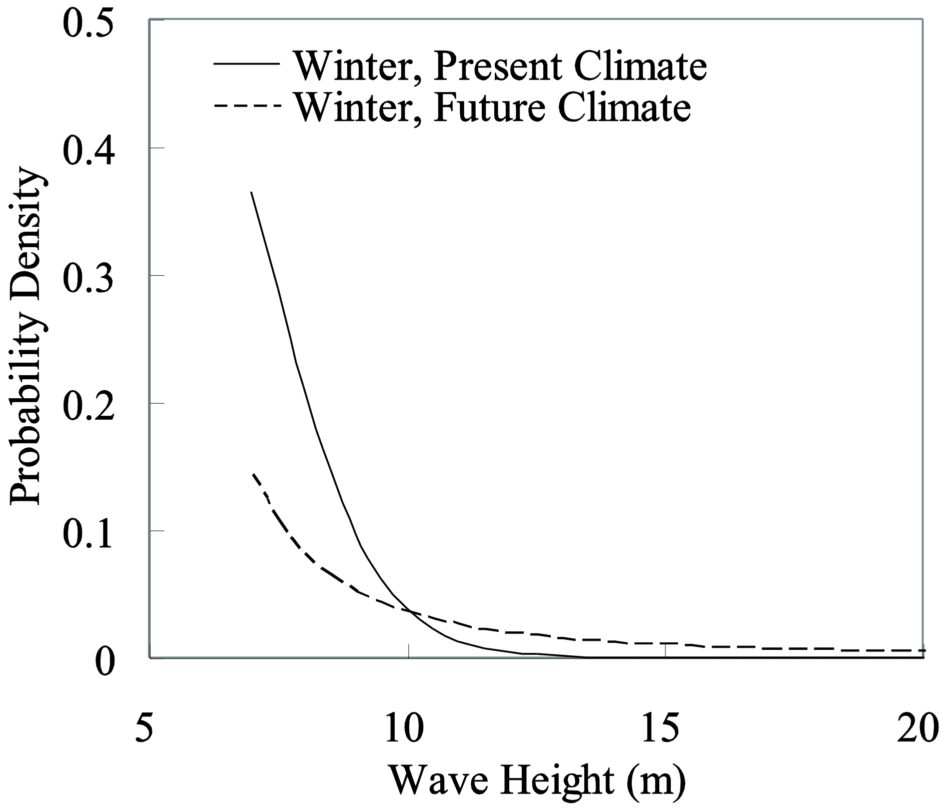


Figure 6 (b). Probability density functions of extreme wave height distribution; (a) summer season; (b) winter season (Mori et al., 2010)

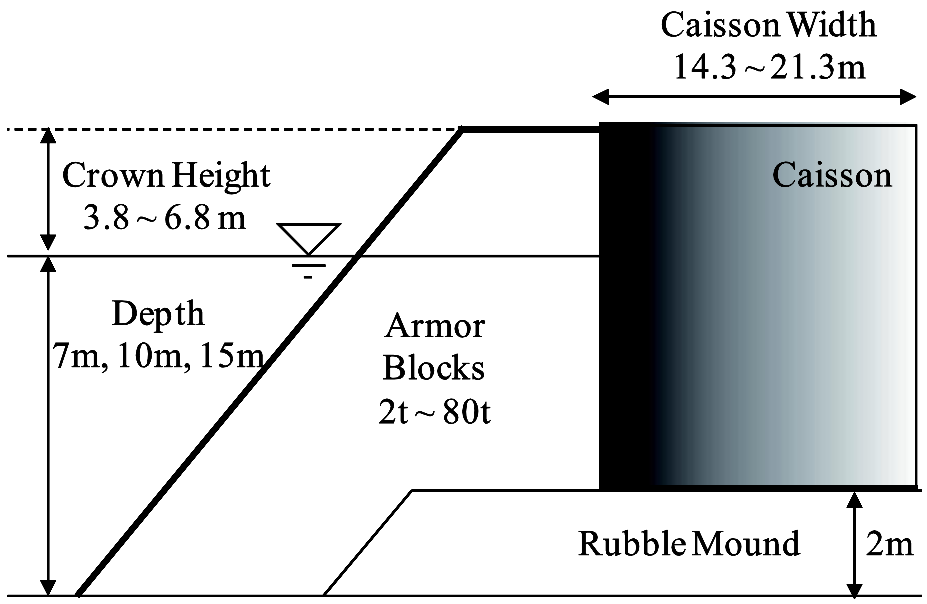


Figure 7. Cross section of model breakwater

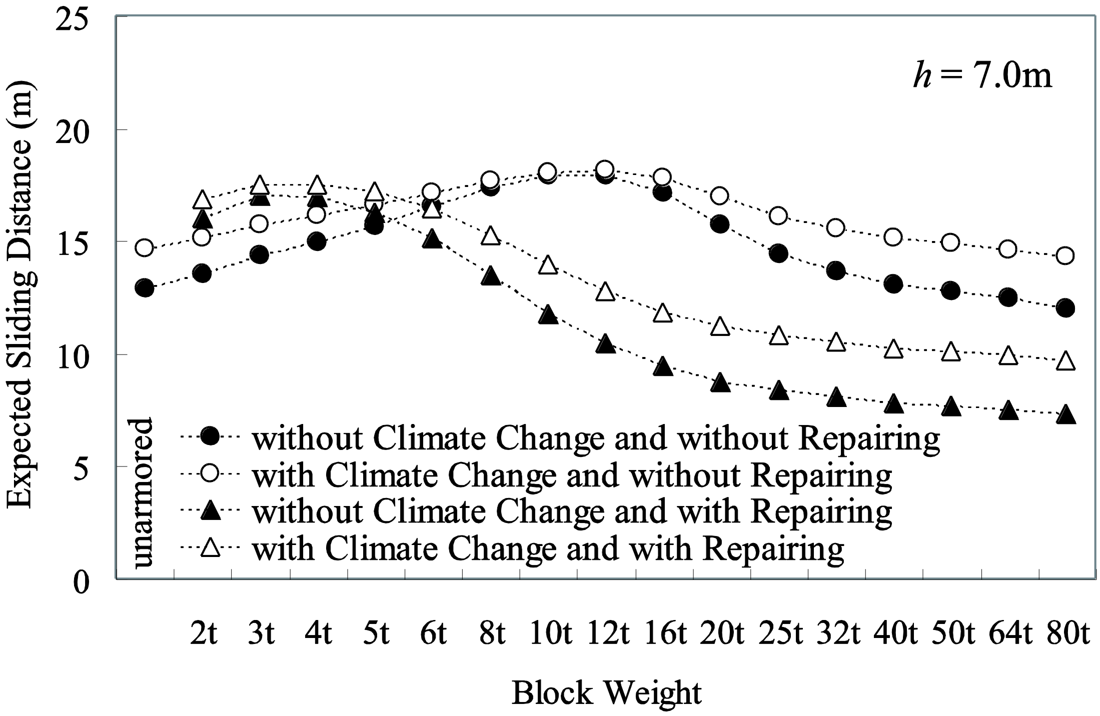


Figure 8 (a). Expected sliding distance of caisson

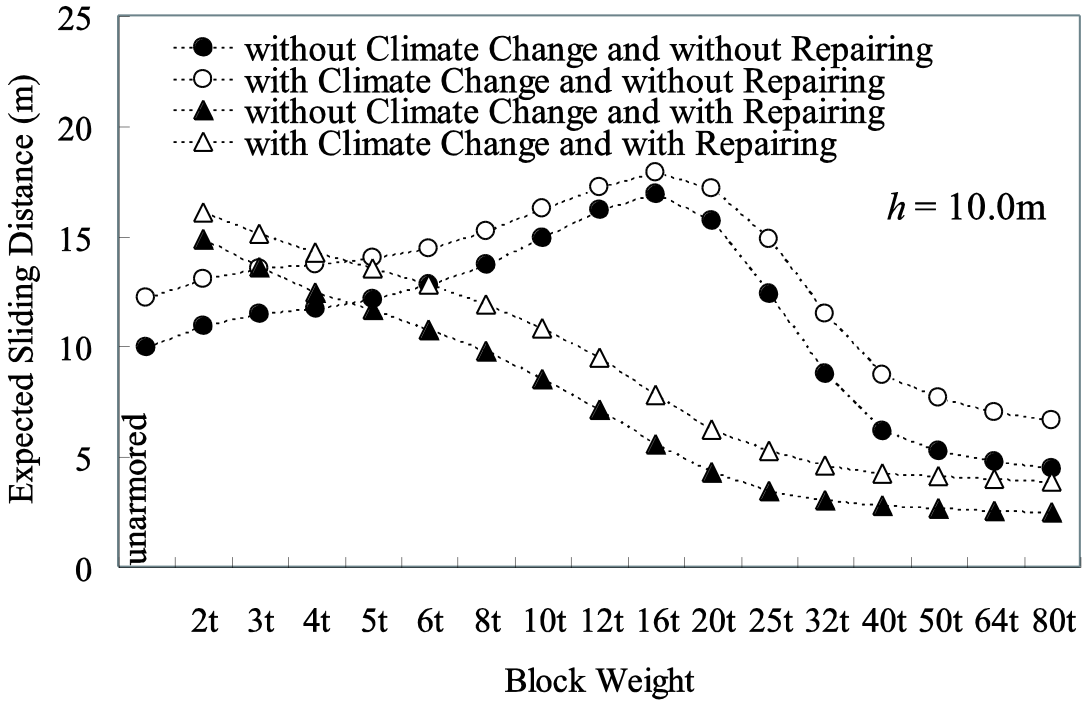


Figure 8 (b). Expected sliding distance of caisson

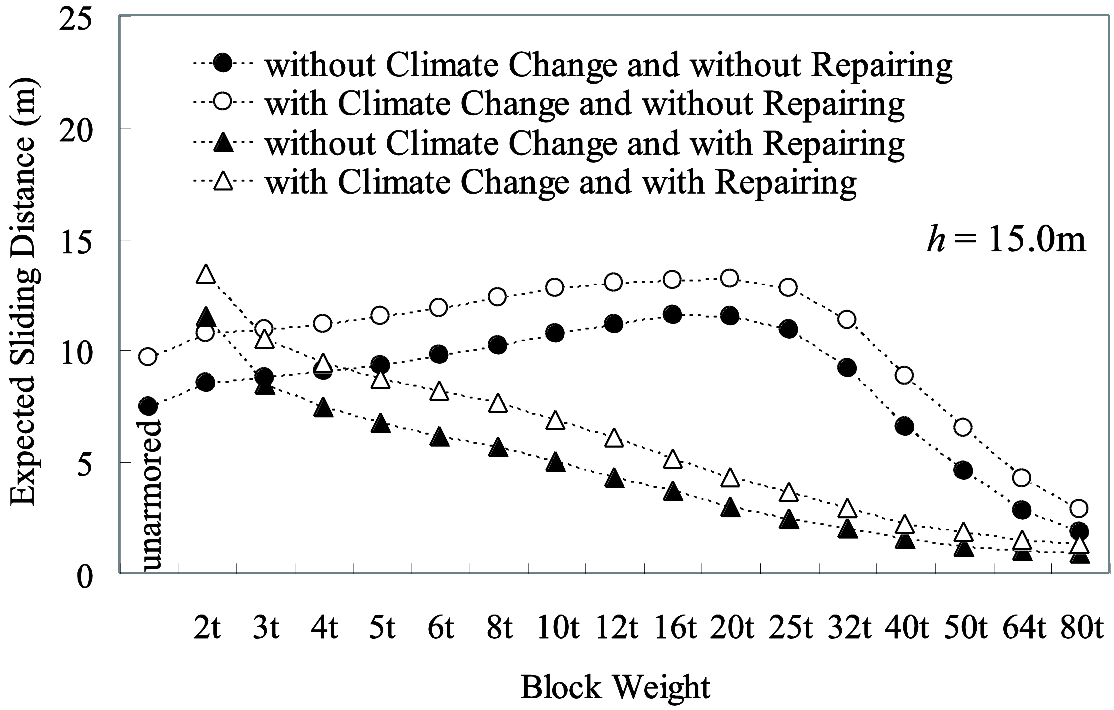


Figure 8 (c). Expected sliding distance of caisson

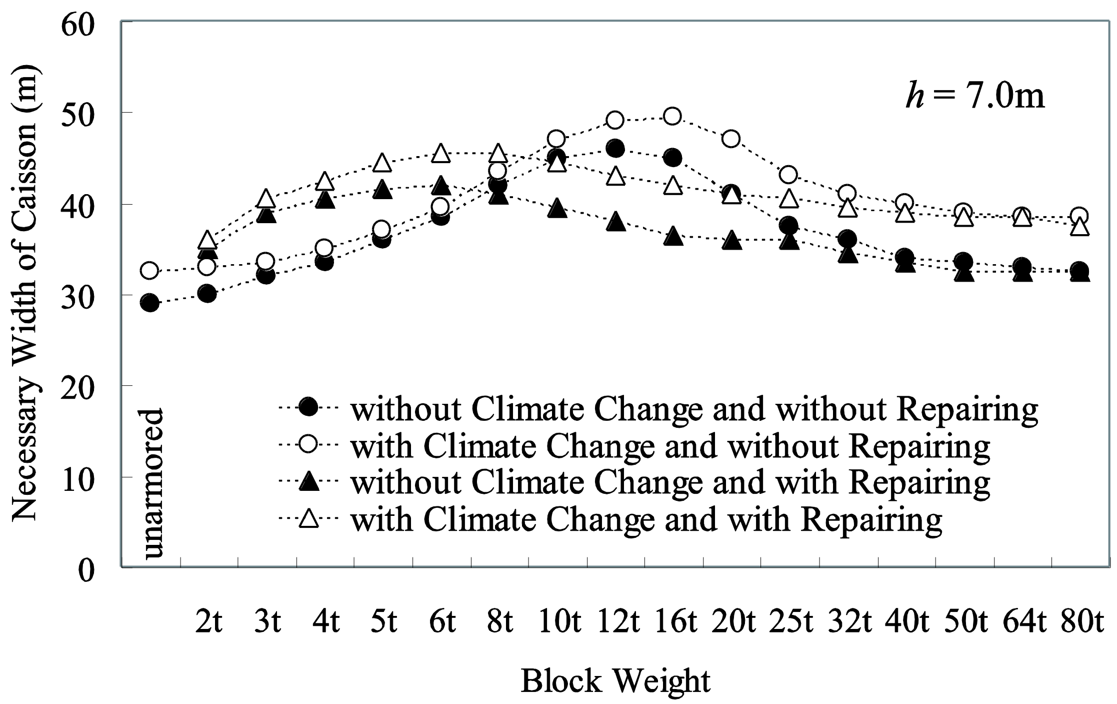


Figure 9 (a). Necessary caisson width

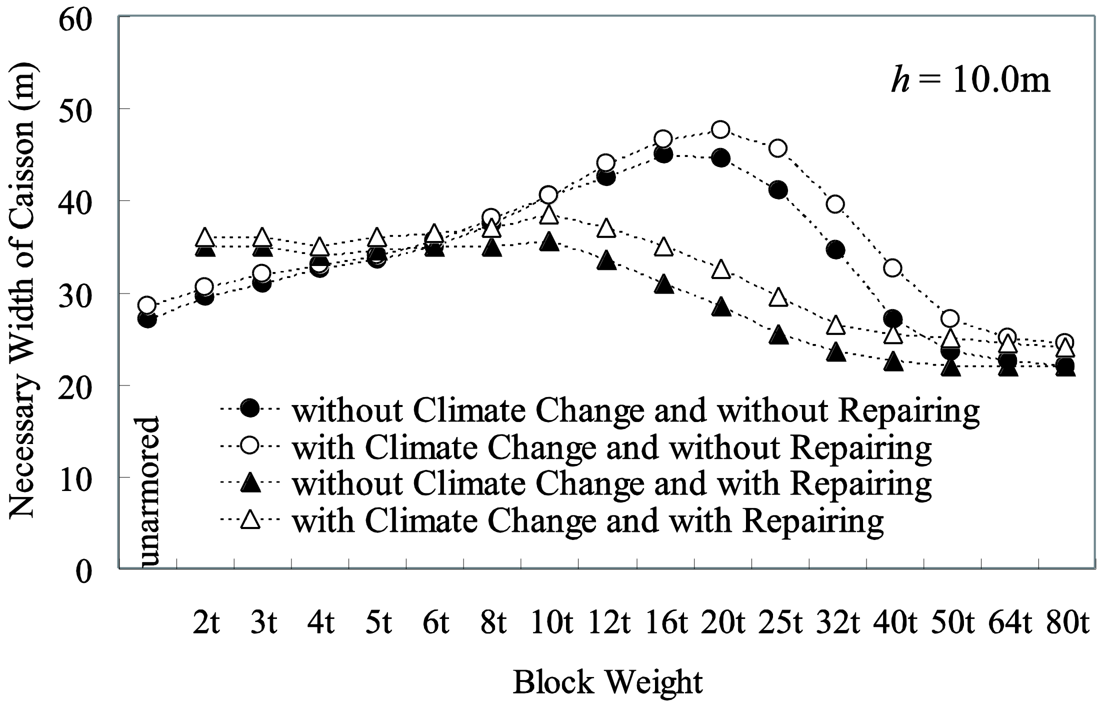
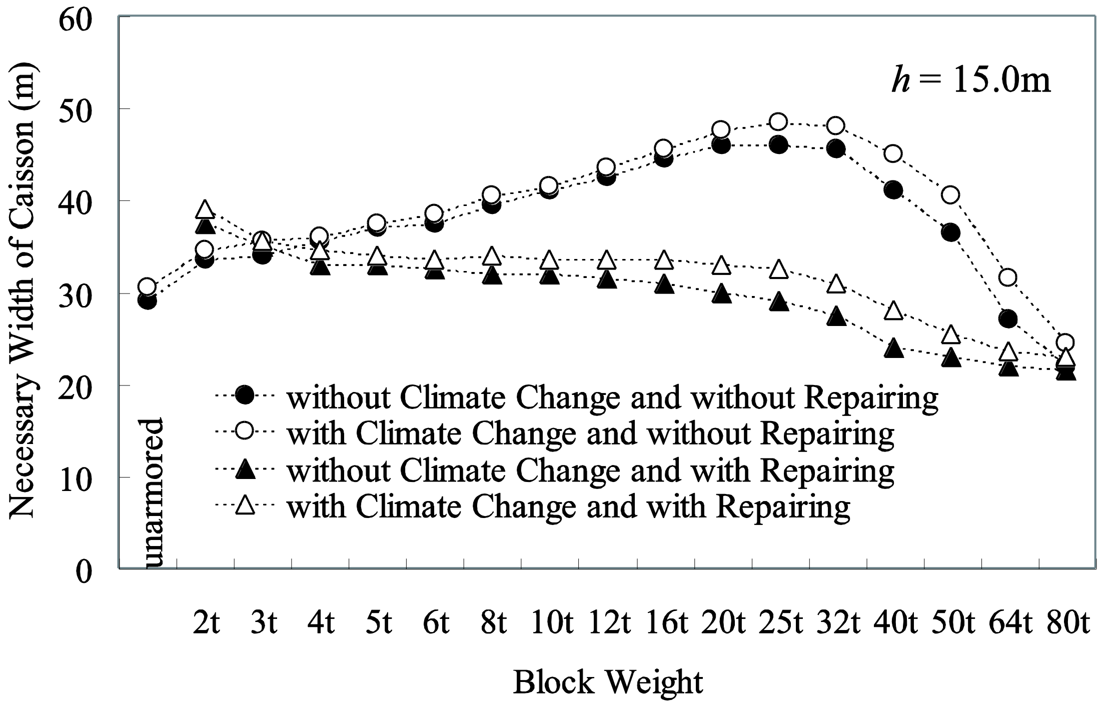


Figure 9 (b). Necessary caisson width



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525 Figure 9 (c). Necessary caisson width

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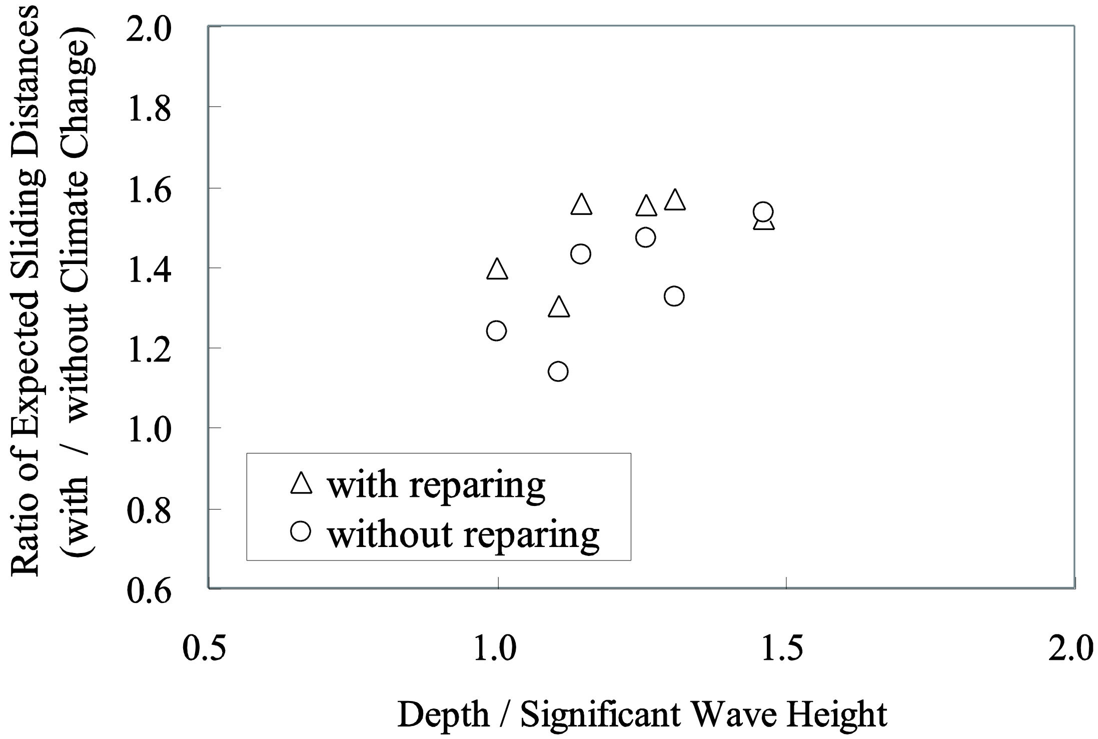

Figure 10 (a). Effects of climate change for expected sliding distance and necessary caisson width

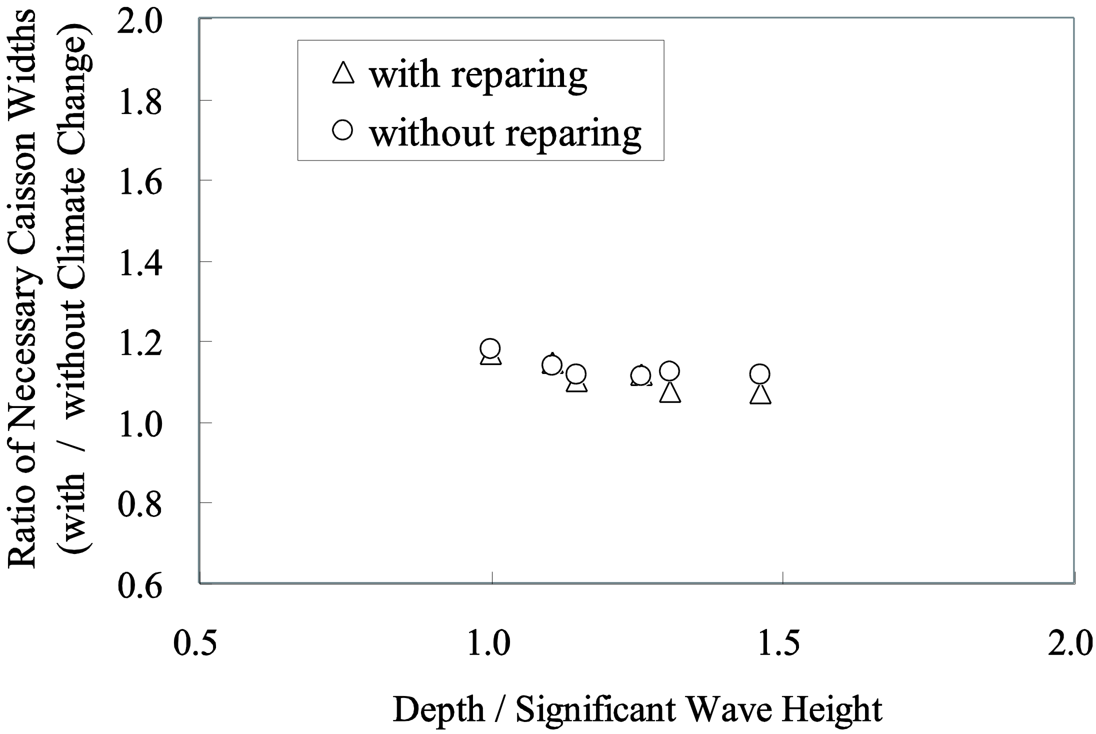

Figure 10 (b). Effects of climate change for expected sliding distance and necessary caisson width

Table 1 Calculation conditions

Item	Value		
Offshore Wave Height Extreme Distribution Function (Summer) in Present Climate	20.07m (λ=0.43) Weibull Distribution with k=1.0, A=4.02, B=7.74		
Offshore Wave Height Extreme Distribution Function (Winter) in Present Climate	10.82m (λ=1.47) Weibull Distribution with k=1.4, A=1.80, B=5.72		
Offshore Wave Height Extreme Distribution Function (Summer) in Future Climate	24.79m (λ=0.53) Weibull Distribution with k=1.0, A=5.25, B=7.58		
Offshore Wave Height Extreme Distribution Function (Winter) in Future Climate	10.84m (λ=0.91) Weibull Distribution with k=1.0, A=1.26, B=6.03		
Water Depth (h)	7m	10m	15m
Width of Caisson when K_r =1.0	16.8m	18.3m	21.3m
Width of Caisson when K_r =0.5	14.3m	16.1m	19.3m
Crown Height of Caisson when K_r =1.0	4.2m	5.2m	6.8m
Crown Height of Caisson when K_r =0.5	3.8m	4.8m	6.4m
Storm Surge Height in Present Climate	2.616m Weibull Distribution with k=1.4, A=0.998, B=-0.248		
Storm Surge Height in Future Climate	3.199m Gumbel Distribution with A=0.646, B=0.358		
Sea Level Rise	0.26m / 100 years		
Duration of a Storm	2 hours		
Service Time	50 years		
Number of Simulation Repetition	10,000 times		
Damage of Concrete Blocks to Be Repaired	5 % of Coverage		

Table 2 Allowable sliding distance and excess probability

		Allowable Excess Probability of Sliding Distance of a Caisson		
		1.0m	0.3m	0.1m
Importance	1: Low	10%	20%	50%
	2: Ordinary	5%	10%	30%
	3: High	2.5%	5%	15%